Injection & Extraction

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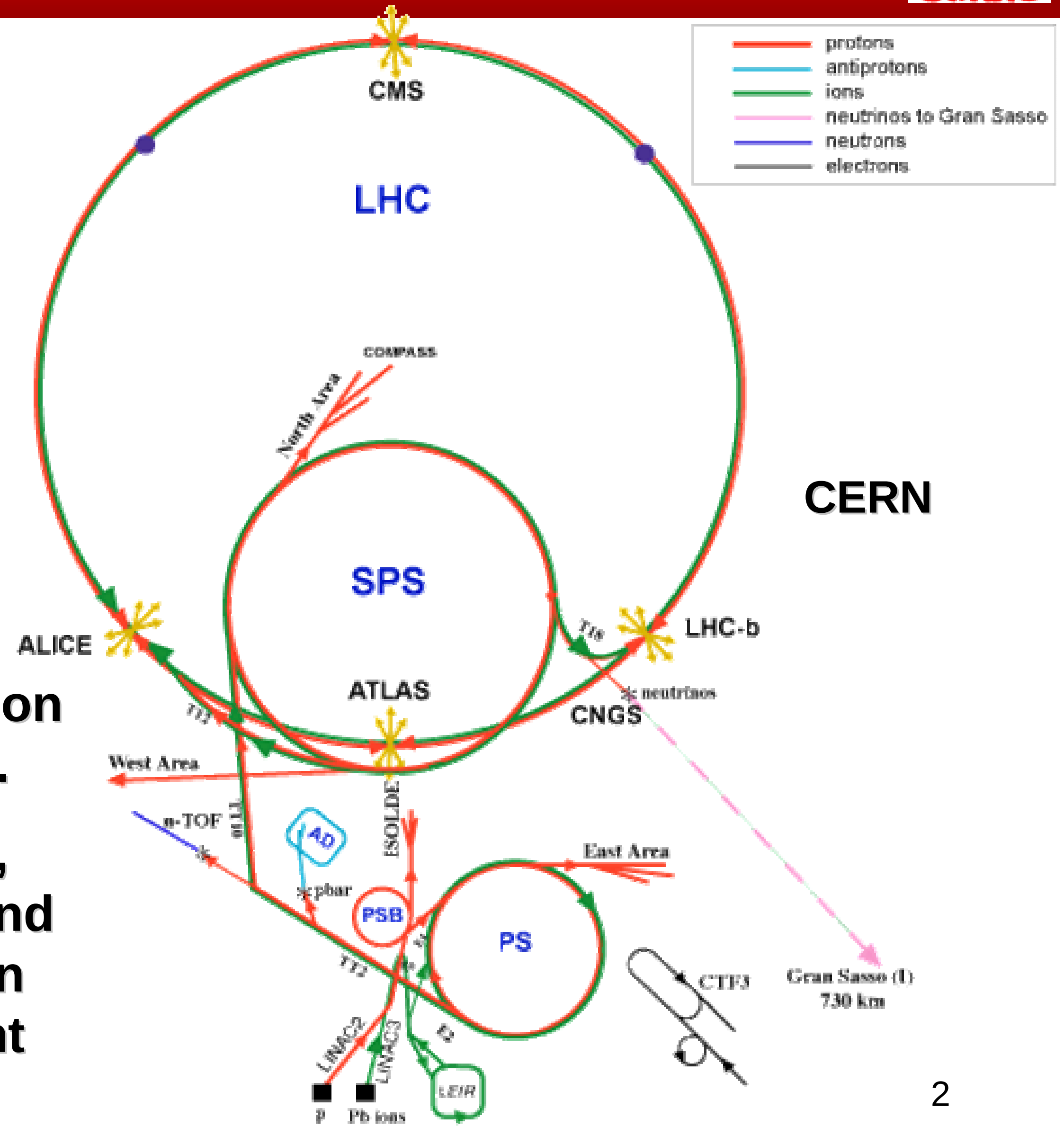
Introduction

- Every accelerator complex that includes a storage ring requires an injection system.
- With increasing complexity, when more than one ring is present, extraction systems make their appearance and more injection systems are added.
- Systems used for injection can be used as well for extraction by simple "mirror reflection".
- In fixed target experiments, where the beam is extracted and sent to a target, the extraction systems can assume different characteristics.



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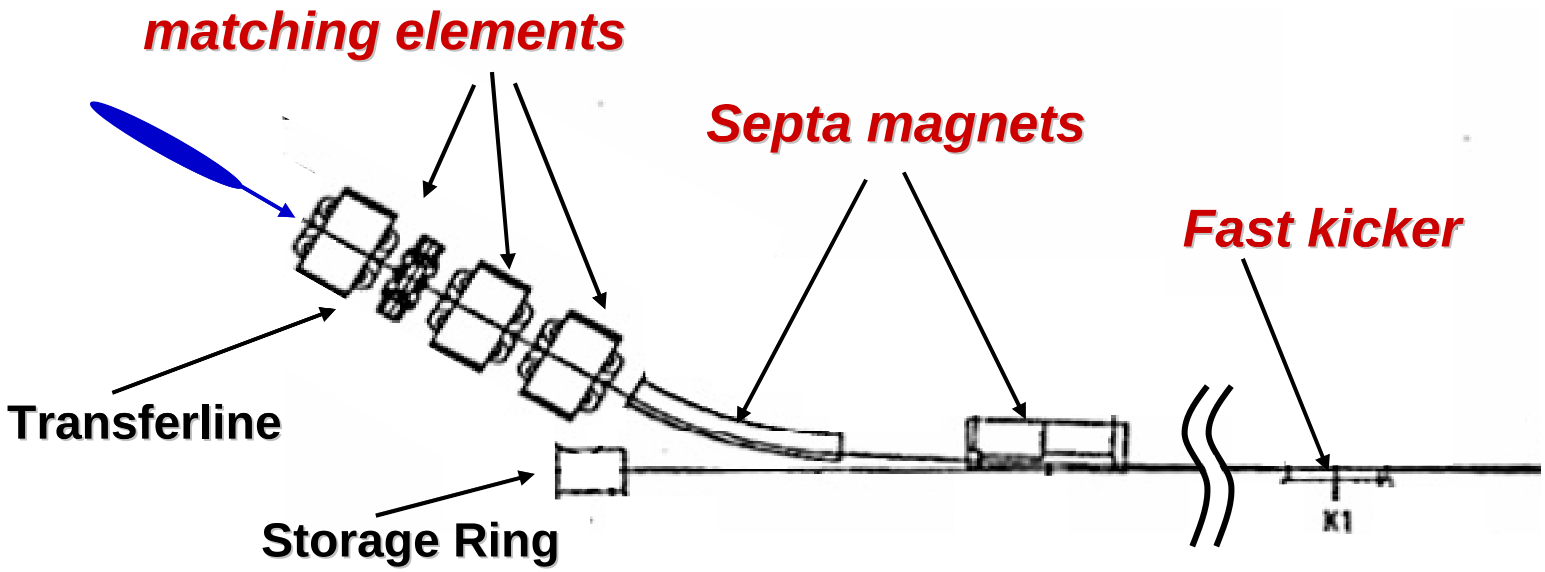
The Typical Injection Section



- ***Matching***: **for an efficient injection, the optical functions in the transfer-line and in the storage ring must be the same at the injection point.**
- ***Septum Magnet***: **Special magnet with a "thin" wall that allows to place the magnet close to the storage ring orbit. Can operate in DC or in pulsed mode.**
- ***Fast Kicker***: **It is the pulsed element that gives the final kick that puts the injected beam on the storage ring orbit. Its pulse must last for less than a ring revolution period for avoiding kick the beam again.**
- **In some injection schemes, a slow orbit bump localized in the septum region, brings the beam closer to the septum wall.**

Injection Matching

By matching at the injection point the optical and the dispersion functions between the transferline and the storage ring, one ensures a "smooth" transition for the beam from the injector to the storage ring.

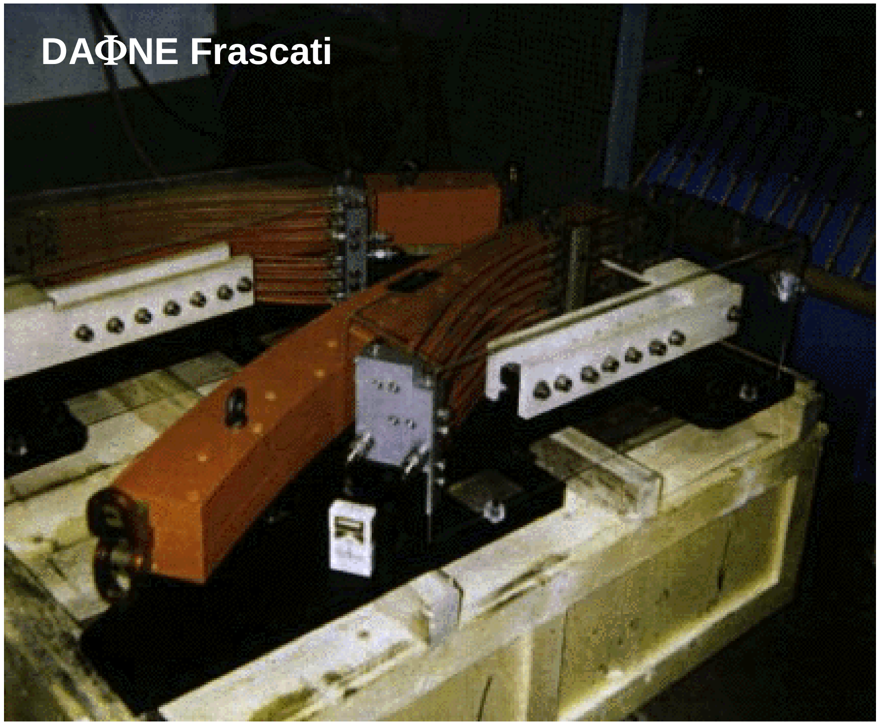
Matching is fundamental for protons and ions, because of the absence of damping.
Any injection error is immediately exported to the storage ring generating emittance growth.

Matching is less critical for electrons and positrons because damping washes-out any injection error within the acceptance of the storage ring

Anyway, for some specific application a good matching is important also for electrons and positrons. For example, *top-off operation* (quasi-continuous injection) in synchrotron light sources and lepton colliders requires a good matching in order to minimize the perturbation (noise) that the injection transient can generate during users' data taking.

Septum Magnet

- Special care in the design must be used for avoiding field leakage that will affect the beam orbit



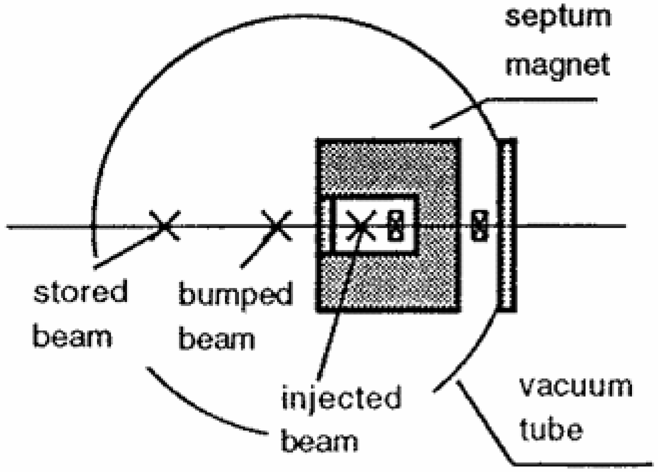
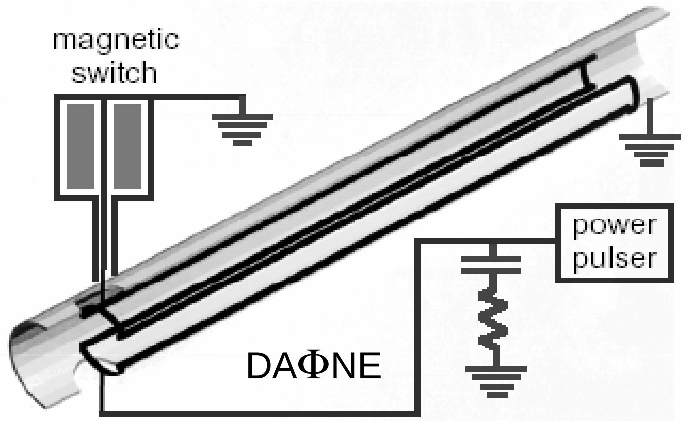


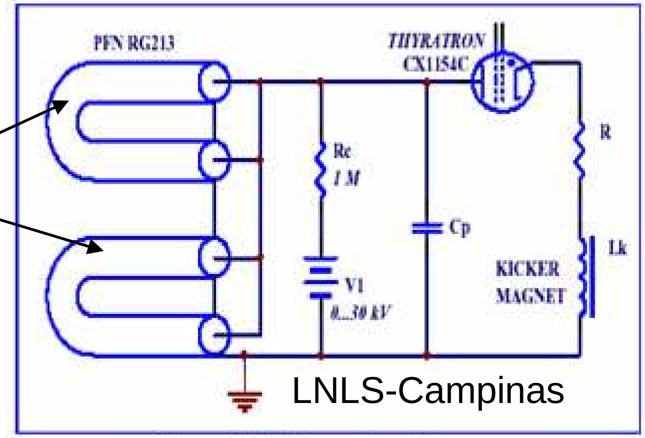
Figure 1. Configuration of APS PAR Septum Magnet

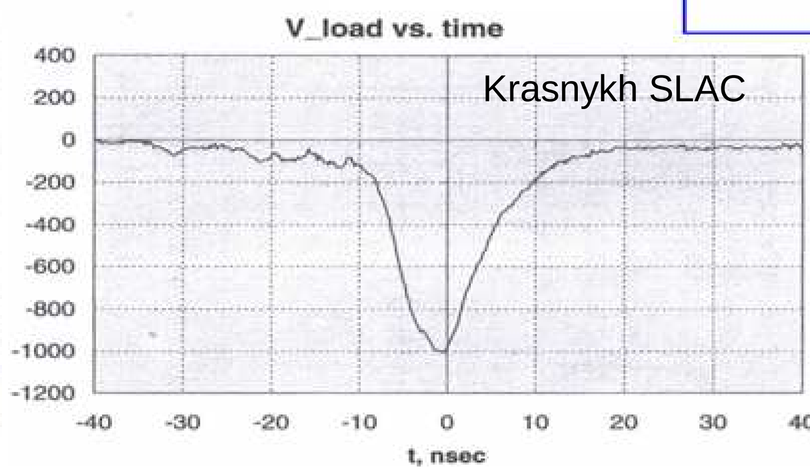
- Septa can be in or out of vacuum, DC or pulsed.

Fast Kickers

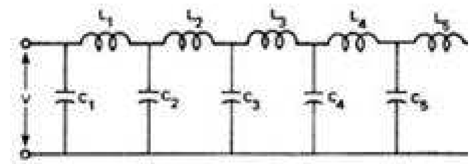


Distributed
PFN





or discrete elements Pulse Forming Network (PFN)

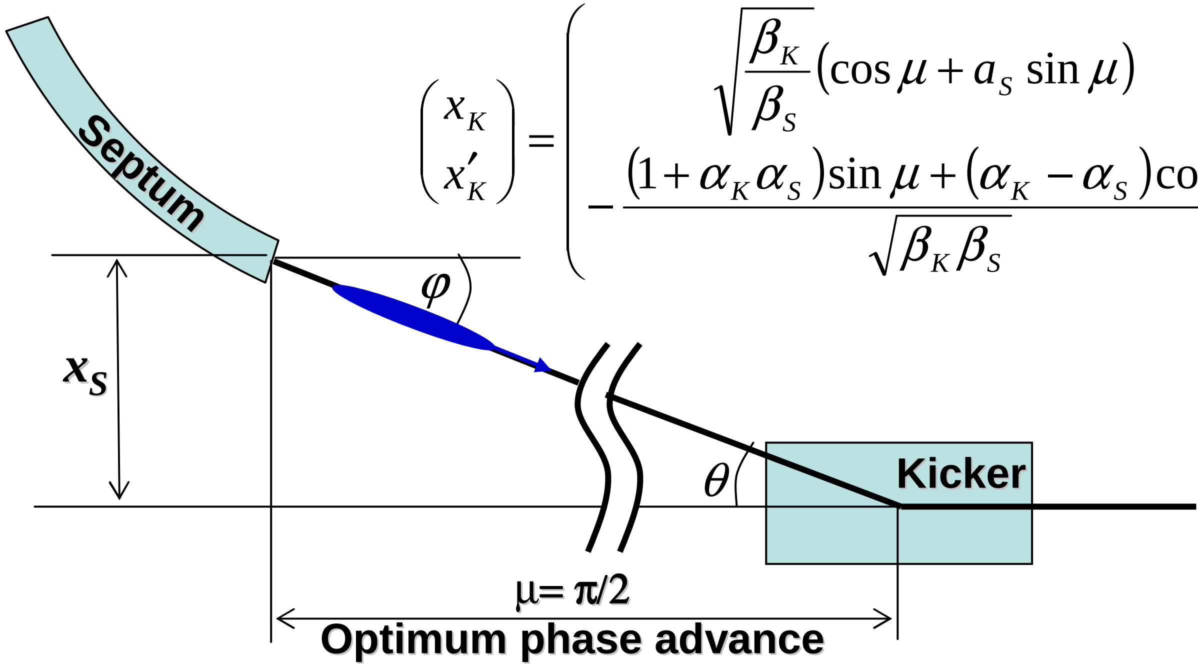


Normally, the kicker pulse duration must be shorter than a revolution period. Typical kickers pulses have ~ 100 ns duration. New machines such as the ILC and other special applications are asking for challenging kickers with few ns pulse duration.

Single Turn Injection

- **The transfer matrix from the septum to the kicker position is given by:**

$$\begin{pmatrix} x_K \\ x'_K \end{pmatrix} = \begin{pmatrix} \sqrt{\dfrac{\beta_K}{\beta_S}}(\cos\mu + a_S \sin\mu) & \sqrt{\beta_K \beta_S}\sin\mu \\ -\dfrac{(1+\alpha_K\alpha_S)\sin\mu + (\alpha_K - \alpha_S)\cos\mu}{\sqrt{\beta_K\beta_S}} & \sqrt{\dfrac{\beta_S}{\beta_K}}(\cos\mu - a_K \sin\mu) \end{pmatrix} \begin{pmatrix} x_S \\ x'_S \end{pmatrix}$$



By imposing that at the kicker $x_K = 0$

$$\boxed{x'_S = -\frac{\cot\mu + \alpha_S}{\beta_S} x_S = \tan\varphi}$$

x_S is defined by the required stay clear at the septum position.

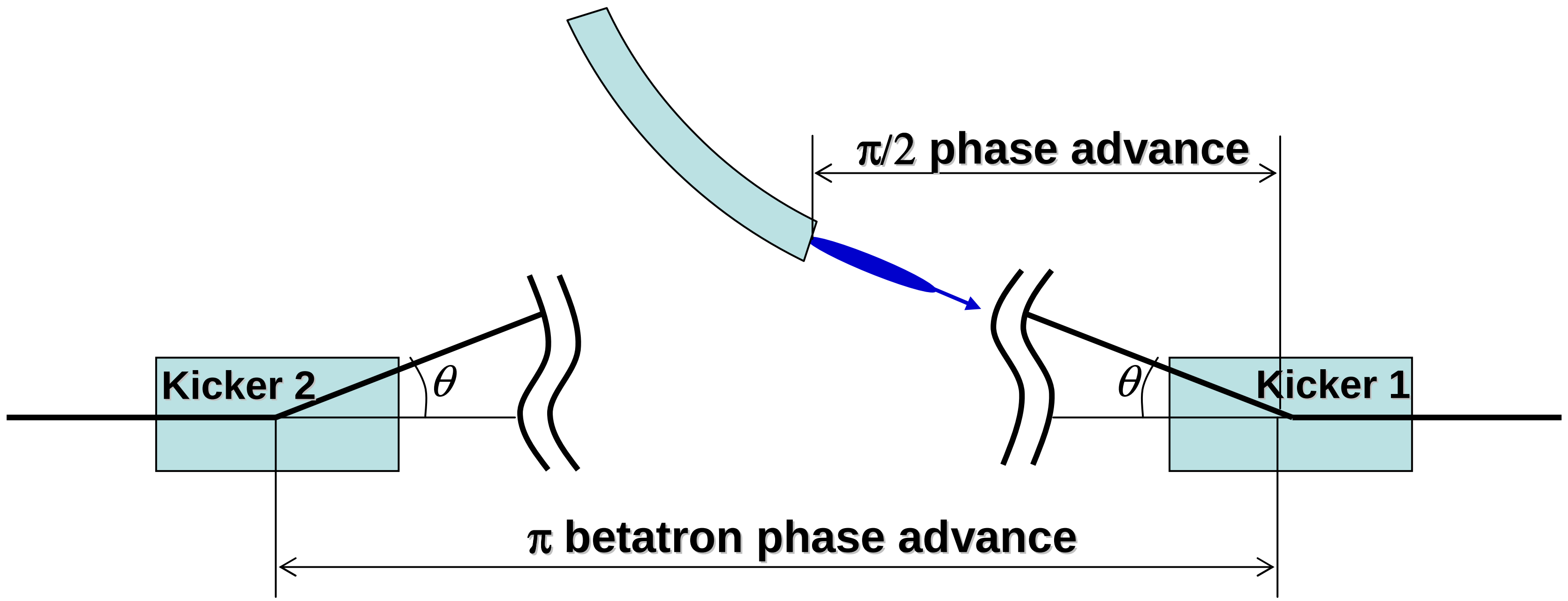
Now using these values at the septum, one can calculate the angle at the kicker position:

$$\boxed{x'_K = -\frac{1}{\sqrt{\beta_S\beta_K}} \frac{x_S}{\sin\mu} = \tan\theta}$$

In order to "place" the beam on the ring reference orbit, the angular kick must be equal to $-\theta$. Note that the minimum θ is obtained when $\mu = \pi/2$

Stacking Beam

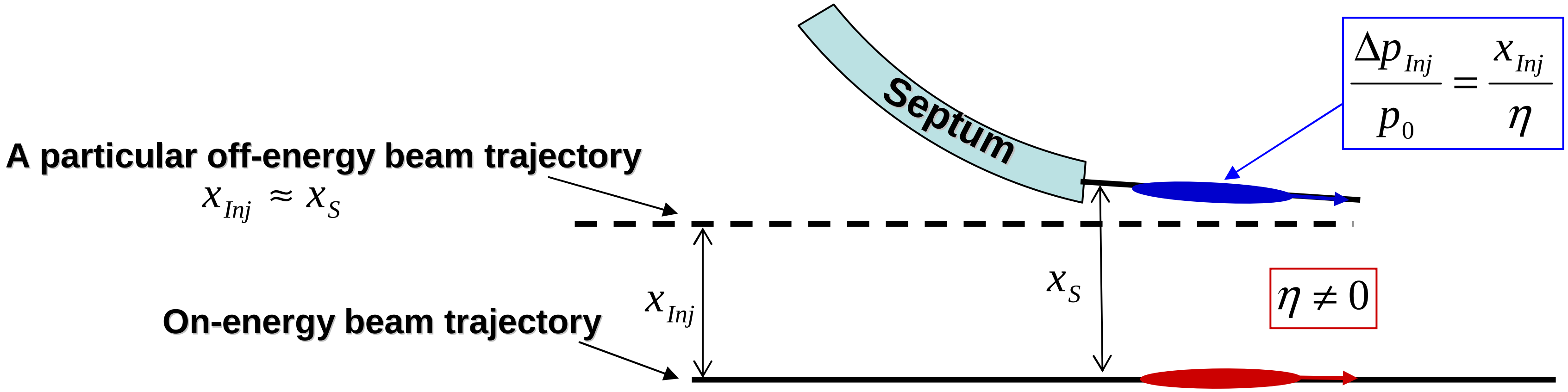
- **If multiple injection in the same bucket is required (*stacking*), the previous scheme can modified as follows:**



- **The new kicker "pre-kicks" the *stored* beam so that when it will pass through Kicker 1 (simultaneously with the injected bunch) it will be placed back on the nominal closed orbit.**

Off-Energy Injection Scheme

• By using a lattice with nonzero horizontal dispersion in the septum area a special injection scheme can be used.



• The injected beam will move on dispersion orbits for few damping times until the radiation damping will bring it at the nominal energy merging with the stored beam.

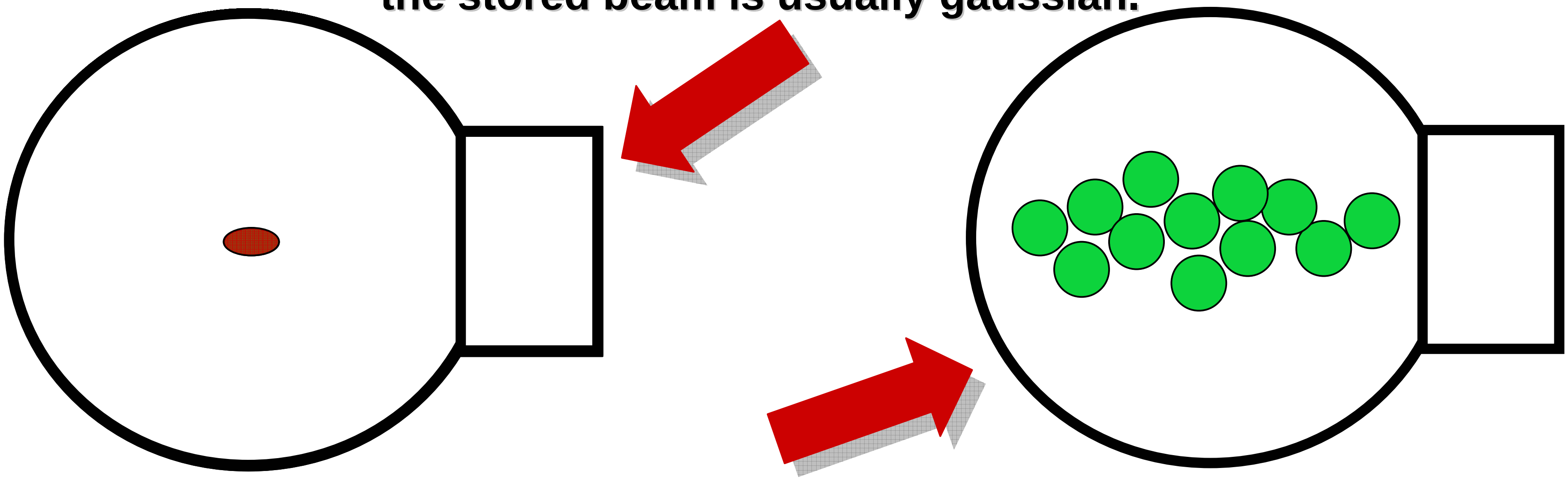
No fast kicker is required. Because of the damping requirement, such a scheme can be used only for electrons and positrons.

Several rings use or successfully tested the off-energy injection schemes. For example APS, HERA, CESR, …

Electrons, Protons and Heavy Ions

• There is a fundamental difference between the two cases of light particles (electron and positrons) and of heavier ones (proton, ions, ...).

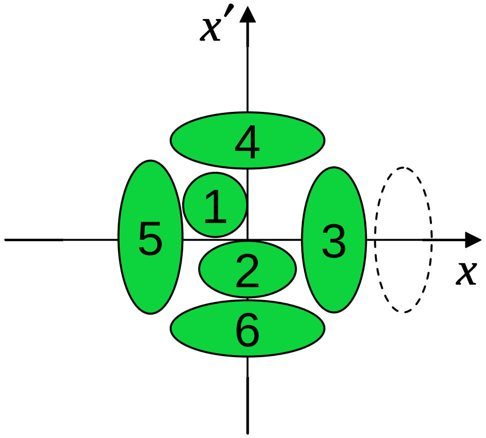
• Electrons and positrons benefit from synchrotron radiation damping. The injected beam within few damping times oscillates down to the stored beam merging with it. Liouville theorem is not violated because synchrotron radiation is a non-Hamiltonian phenomenon. The equilibrium distribution of the stored beam is usually gaussian.



• For protons and ions Liouville theorem does not allow the "merging" of the beams and one needs to use special schemes that allow to fill the whole available transverse acceptance. The final distribution is "irregular".

Multiturn Injection for Protons and Ions

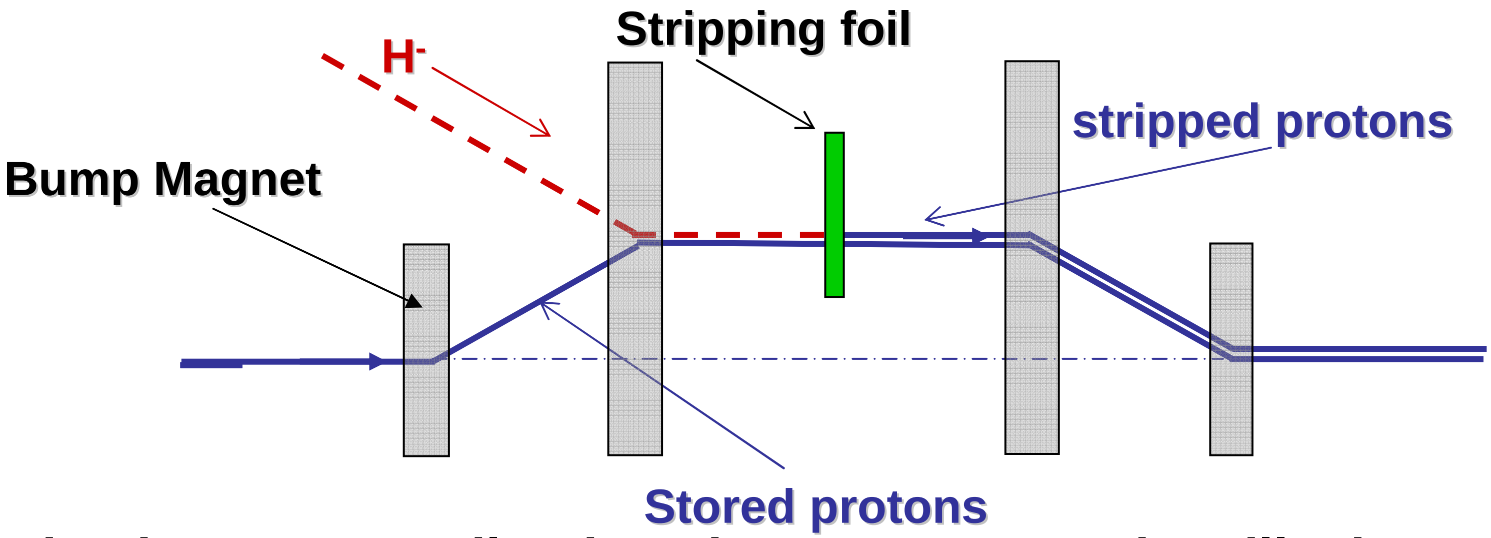
- The typical scheme uses a *fast orbit bump* in the septum area in combination with a lattice tuned on a *resonant betatron tune*:
  - New beam is injected in the same bucket every revolution period.
    - The bump is properly shifted between the injected bunches.
    - While the resonant tune generates a constant rotation in the transverse phase space.
- By selecting the proper combination of tune and "speed" of the bump, it is possible to fill the phase space in an almost uniform way (beam "painting").
  - For example, for a fractional horizontal tune of 0.25:



- The first of such schemes was used in 1953 at the COSMOTRON Cyclotron in Brookhaven
- Longitudinal painting is also possible by properly changing the energy of the injected beam every injection cycle.

Charge Exchange Injection

On 1963, G.I. Budker and G.I. Dimov at Novosibirsk conceived a new multiple injection scheme involving H^- ions:



- **Stripping is a-non Hamiltonian phenomenon so Liouville theorem does not apply and multiple injections on the same phase space area are allowed.**
- **The stripping foil must be very efficient in removing the electrons from the negative ions (~99%) and at the same time the perturbation the foil induces on the stored proton beam should be as small as possible.**
- **Carbon and aluminum ~ 10 to 100 μm thickness are typically used.**

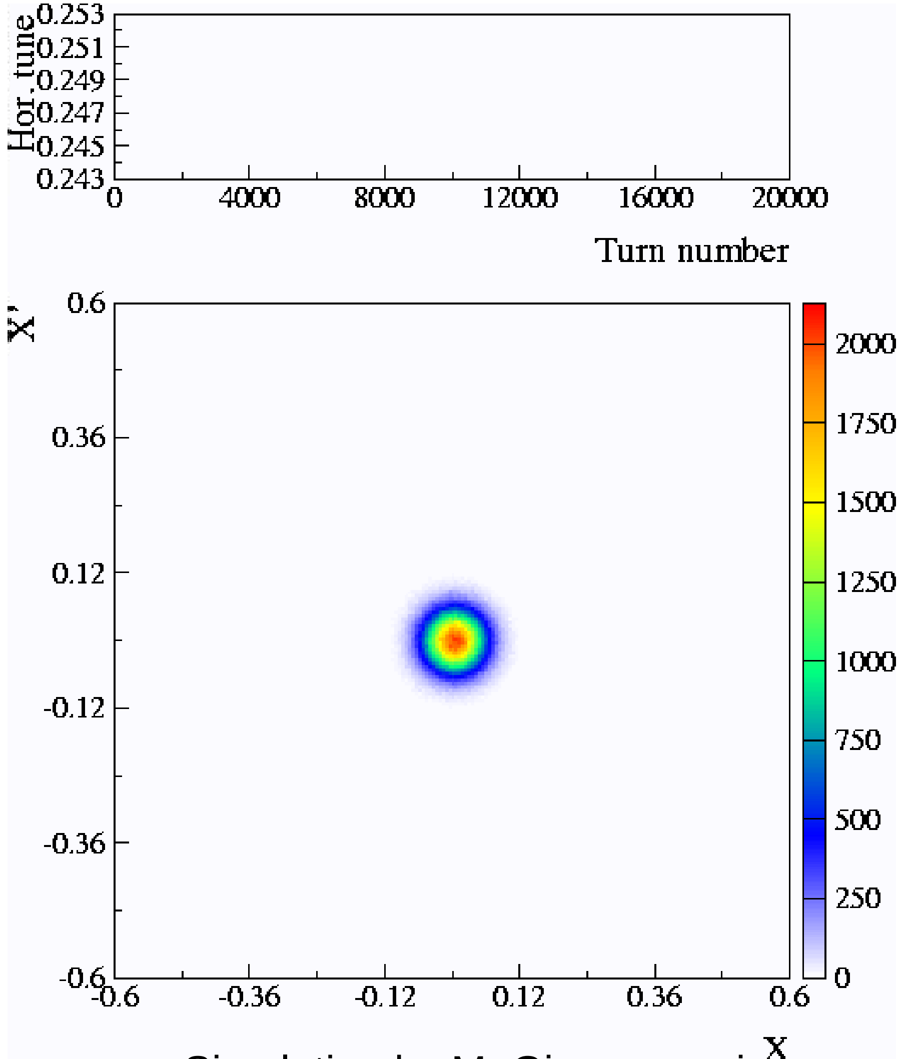
Exploiting Betatron Resonances

- By setting the lattice on tune resonances, one can generate "islands" in the phase space. The example shows a 4th order resonance

- Resonances are usually dangerous and carefully avoided in designing and operating a storage ring.

- Anyway, there are exceptions.

- In fact, resonances and phase space islands have been efficiently exploited for both injecting or extracting the beam

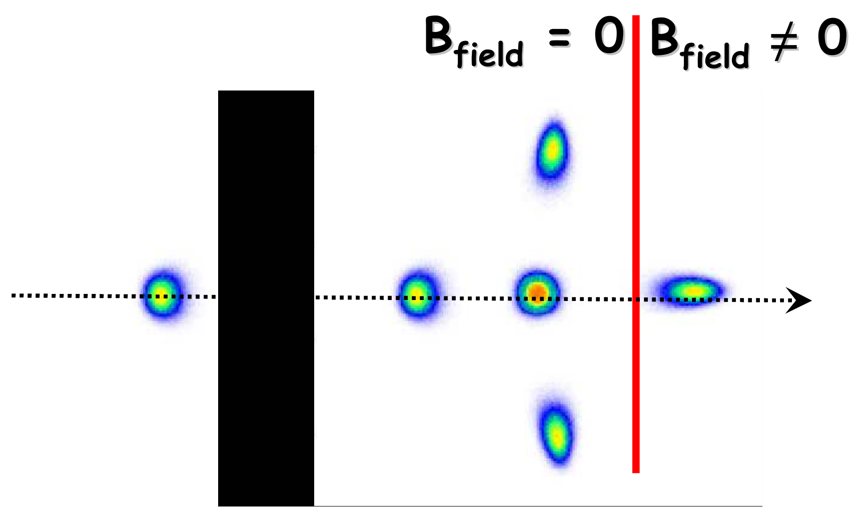


Simulation by M. Giovannozzi

Resonant Schemes

• The 4th resonance shown in the previous viewgraph can be used for a resonant extraction scheme for example.

• The simulation shows a slow bump bringing the beam close to the septum wall and a fast kick extracting the beam from the storage ring to other side of the septum wall into the transferline.



Simulation by M. Giovannozzi

• Schemes like this are studied for *multi-turn extraction* as required from some fixed target applications. In the example, because of the 0.25 tune, the islands rotate 90 deg on every turn and are extracted in four turns. The central core is then extracted by the fast kicker.

• Injection schemes exploiting betatron resonances, have been successfully tested in few storage rings. In the AURORA ring from Sumitomo for example, they use a half-integer resonance scheme.

References

• **G.H. Rees, *Injection, CAS - 5th General accelerator physics course, CERN 94-01***

• **Rende Steerenberg, *talk at AXEL – 2005, March 17, 2005.***

Possible Homeworks

- In designing a single turn injection system, we have the choice of locating our kicker at two different positions, say A and B. At A the betatron phase advance from the septum position is $\pi/2$ and the horizontal beta function is 3m. AT B the phase advance is $5/8\ \pi$ but the beta function is 7 m. Where would you place the kicker? If the required stay clear at septum imposes a distance between the injected beam trajectory and the closed orbit of 2 cm, what is the required angular kicker for storing the beam? The beta function at the septum is 5 m.

- If we want to upgrade the above system for stacking the beam by placing a second kicker in the mirror symmetry point with respect of the septum magnet. What would it be the required angular kicker in the second kicker?

- If the RF frequency in our ring is 500 MHz and the harmonic number is 400, what will be the maximum pulse duration that the kicker pulse can have?